Measurement of the ^{214}Bi spectrum in the energy region around the Q-value of ^{76}Ge neutrinoless double-beta decay.

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Abstract

In this work we present the results obtained measuring the ^{214}Bi spectrum from a ^{226}Ra source with a high purity germanium detector. Our attention was mostly focused on the energy region around the Q-value of ^{76}Ge neutrinoless double-beta decay (2039.006 keV). The results of this measurement are strongly related to the first indication for the neutrinoless double beta decay of ^{76}Ge, given by a recent analysis [1, 2, 3, 4] of the data collected during ten years of measurements from the HEIDELBERG-MOSCOW experiment.

1 Introduction

A recent analysis [1, 2, 3, 4] of the data collected during ten years of measurements by the HEIDELBERG-MOSCOW experiment, at the Gran Sasso Underground Laboratory, yields a first indication for the neutrinoless double beta decay of ^{76}Ge. An important point of this analysis is the interpretation of the background, in the region around the Q-value of the double beta decay (2039.006(50) keV, see [5]), as containing several weak photopeaks. It was suggested in [1], and has been shown in [2, 3, 4], that four of these peaks are produced by a contamination from the isotope ^{214}Bi, whose lines are present throughout the HEIDELBERG-MOSCOW background spectrum.

In a following paper [6], some criticisms to [1, 2, 3, 4] were raised. One of the main points mentioned was that the intensities of the weak bismuth lines between 2000 and 2080 keV, as deduced from the intensities of the strong

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lines and the branching ratios from the Table of Isotopes [8], were much lower than observed in the HEIDELBERG-MOSCOW background spectrum. It was shown, in a reply to these criticisms [7], that the simple estimate of [6] about the intensities of the weak bismuth lines was not correct. It did not take into account the long-known spectroscopic effect of the true coincidence summing (TCS, see [10]) and, most important, the localization of the bismuth contamination inside the HEIDELBERG-MOSCOW experiment.

With a careful simulation of the experimental setup, it was shown that, if the contamination is localized in the copper cap of the detectors, the expected values for the four peak-areas in the region of interest were compatible (within two sigma) with the measured values (see Table 1 of [7] and Table 7 in [3, 4]).

In this work we performed a *measurement* of a ^{226}Ra source with a high-purity germanium detector. The aim of this work is to study the spectral shape of the lines in the energy region from 2000 to 2100 keV and, most important, to show the difference in this spectral shape when changing the position of the source with respect to the detector, and to verify the effect of TCS for the weak ^{214}Bi lines seen in the HEIDELBERG-MOSCOW experiment experiment.

The activity of the ^{226}Ra source is 95.2 kBq. The isotope ^{226}Ra appears in the ^{238}U natural decay chain and from its decays also ^{214}Bi is produced. The γ-spectrum of ^{214}Bi is clearly visible in the ^{226}Ra measured spectrum. We also performed a simulation of our measurement with the GEANT4 simulation tool and we find a good agreement between the simulation and the measurement. The results of this measurement confirm that the criticism by [6] is wrong and the analysis of [1, 2, 3, 4] of the double beta experiment is correct.

2 The Isotope ^{214}Bi and the TCS Effect

^{214}Bi is a naturally occurring isotope: it is produced in the ^{238}U natural decay chain through the β^- decay of ^{214}Pb and the α decay of ^{218}At. With a subsequent β^- reaction, ^{214}Bi decays then into ^{214}Po (the branching ratio with respect to the α decay into ^{210}Tl is 99.979%). The decay, however, does not lead directly to the ground state of ^{214}Po, but to its excited states. From the decays of those excited states to the ground state we obtain the well known γ-spectrum of ^{214}Bi which contains more than hundred lines.

As one can see in Table 1, in the energy region around the Q-value of the $0\nu\beta\beta$ decay (2000-2100 keV), four γ-lines and one E0 transition with energy 2016.7 keV are expected. The E0 transition can produce a conversion electron or a electron-positron pair but it could not contribute directly to the γ-spectrum in the considered energy region if the source is located outside the detector active volume.

Energy (keV)	Intensity (%)
2010.71 (15)	0.050 (6)
2016.7 (3)	0.0058 (10)
2021.8 (3)	0.020 (6)
2052.94 (15)	0.078 (11)
2089.7 (2)	0.050 (6)

Table 1: γ-lines from ^{214}Bi in the energy region from 2000 to 2100 keV around the Q-value of ^{76}Ge. The number in parenthesis is the error on the least significant digit (see Table of Isotopes [8]).

The intensity of each line is defined as the number of emitted photons, with the corresponding energy, per 100 decays of the parent nuclide.

When coming to the measurement, we have to consider the efficiency of the detector (which depends on the size of the detector and on the distance source-detector) and the effect called True Coincidence Summing (TCS). The TCS effect is described in detail in [10]. The lifetimes of the atomic excited levels are much shorter than the resolving time of the detector. If two gamma-rays are emitted in cascade, there is a certain probability that they will be detected together. If this happens, then a pulse will be recorded which represents the sum of the energies of the two individual photons, instead of two separated pulses with different energies. The TCS effect can result both in lower peak-intensity for full-energy peaks and in bigger peak-intensity for those transitions whose energy can be given by the sum of two lower-energy gamma-rays. In our case, the lines at 2010.7 keV and 2016.7 keV (see Fig. 1) can be given by the coincidence of the 609.312 keV photon (strongest line, intensity = 46.1%) with the 1401.50 keV photon (intensity = 1.27%) or with the 1407.98 keV photon (intensity = 2.15%).

The degree of TCS depends on the probability that two gamma-rays emitted simultaneously will be detected simultaneously. This is a function of the geometry and of the solid angle subtended at the detector by the source. For this reason, the intensities of the two lines mentioned above (2010.71 keV and 2016.7 keV) are expected to depend on the position of the source with respect to the detector.

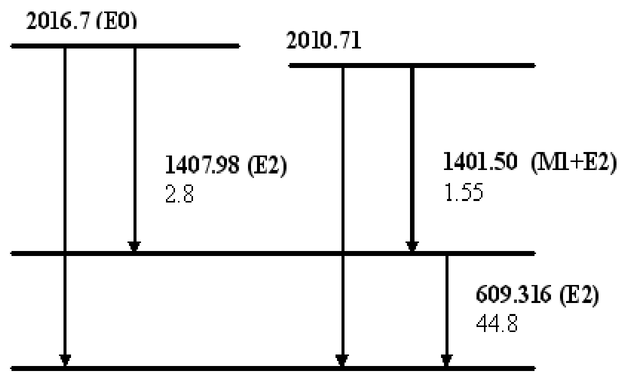

Figure 1: Simplified decay scheme for the two transitions 2010.7 keV and 2016.7 keV in ^{214}Po, formed by β^- decay of ^{214}Bi.

3 The measurement

The ^{226}Ra γ-ray spectra were measured using a γ-ray spectroscopy system based on an HPGe detector installed in the operation room of the HEIDELBERG-MOSCOW experiment in Gran Sasso Underground Laboratory, Italy. The coaxial germanium detector has an external diameter of 5.2 cm and is 4.9 cm high. The distance between the top of the detector and the copper cap is 3.5 cm. The relative detection efficiency of the detector is 23% and the energy resolution is 3.6 keV for the energy range 2000-2100 keV.
The electronics system consists of a linear spectroscopy amplifier and an ORTEC MCA board installed in a personal computer. The γ-ray pulses from the preamplifier are shaped into semi-Gaussian by the amplifier. To reduce pile-ups the shaping time 2 μsec was chosen. The energy threshold was set at 120 keV to reduce the MCA dead-time. Maximum count rate and dead-time during the measurements were not higher then 10000 cps and 13%, respectively.

In a first step the source was positioned on the top of the detector, directly in contact with the copper cap (close geometry). In a second step the source was moved 15 cm away from the detector cap (far geometry). Fig. 2 shows the experimental setup. To collect a high statistics in the considered region, the duration of the measurements were 60000 sec and 170000 sec for close and far geometries, respectively. The spectra were processed by the Aptec-Demo MCA Analysis Software, allowing separate overlapping γ-lines.

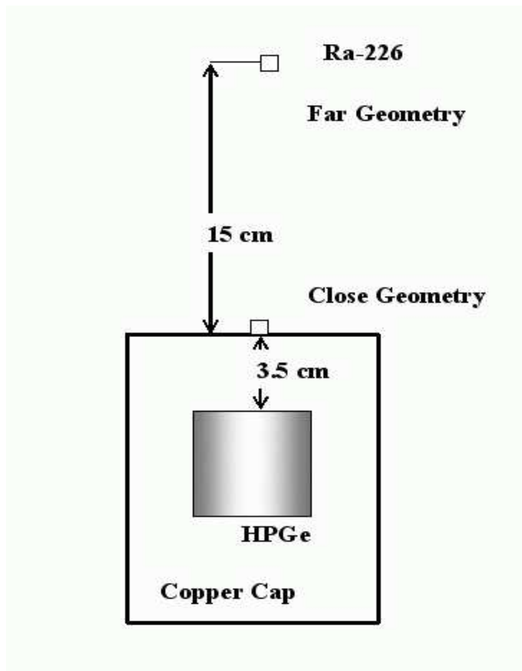

Figure 2: Detector setup for the far geometry and the close geometry measurements.

4 Results and Discussions

The full measured spectra of the Ra source are shown in Fig. 3, the energy region of interest is shown in Fig. 4. One can easily appreciate the difference in the spectral shape when going from the far geometry (bottom spectrum) to the close geometry (upper spectrum). In the first case (far), the line at 2016.7 keV is completely absent and the relative intensities of the other four lines are in perfect agreement (see Tables 2 and 3) with the numbers given in the Table of Isotopes. In the second case (close), the line at 2016.7 keV is clearly visible and the relative intensities of the lines are globally modified (see again Tables 2 and 3).

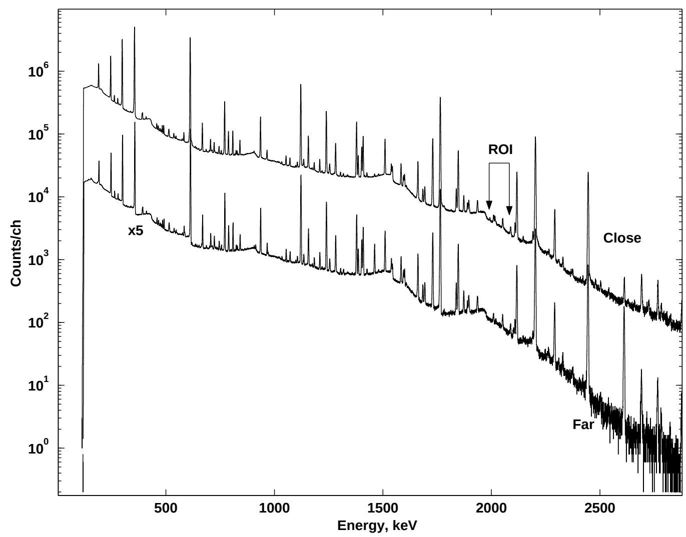

Figure 3: Full measured ^{226}Ra spectra. The region of interest (ROI) is shown in detail in Fig. 4.

A simulation with the GEANT4 Monte Carlo simulation tool, which reproduces the precise geometry of the experimental setup, has been performed and compared to the results of the measurements. Only the contribution of the isotope ^{214}Bi was included in the simulation. 5×10^7 ^{214}Bi decays were started for the close geometry simulation and 5×10^8 events were started in the case of far geometry. The data-file containing the complete ^{214}Bi γ-spectrum was taken from the ENSDF library and is available on the net [9]. The results of the simulation are reproduced in Fig. 5. Note that the simulated spectrum does not take into account the resolution of the detector. The agreement between the simulated spectra and the measured ones with respect to the relative intensities of the lines is clear. A comparison of the intensities is given in Table 2 for the far geometry and in Table 3 for the close geometry.

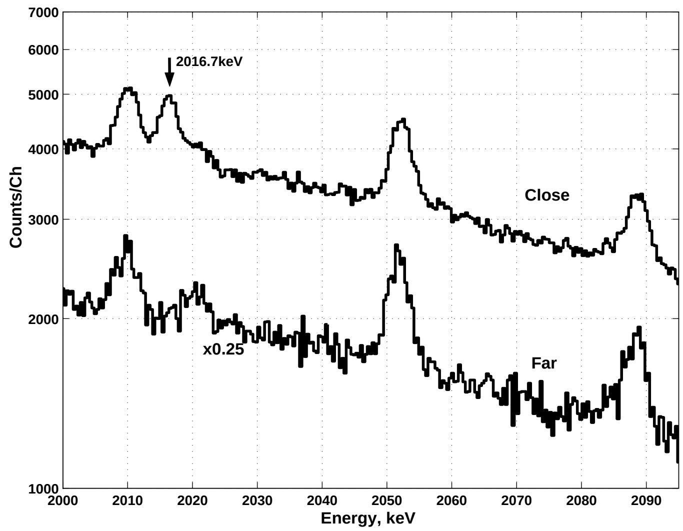

Figure 4: Measured ^{226}Ra spectrum in the energy range from 2000 to 2100 keV. The upper spectrum corresponds to the close geometry, the bottom spectrum to the far geometry (see text). The weak lines from ^{214}Bi are nicely visible, together with the effect of the true coincidence summing at 2010.71 keV and 2016.7 keV.

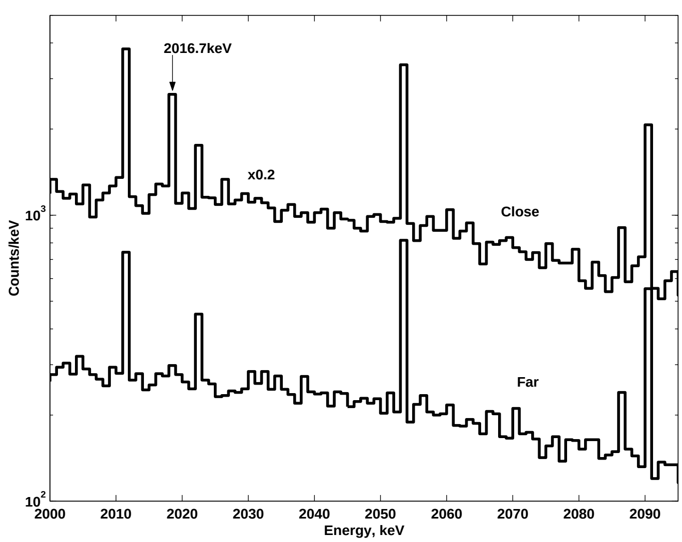

Figure 5: Simulated ^{214}Bi spectrum in the energy range from 2000 to 2100 keV. The upper spectrum corresponds to the close geometry, the bottom spectrum to the far geometry (see text).

Far Geometry (source 15 cm away from the detector cap)

Energy (keV)	Rel.Int.(TOI)(*)	Rel.Int.(Exp.)	Rel.Int.(Sim.)
2010.71	0.64 ± 0.17	0.68 ± 0.12	0.80 ± 0.09
2016.7	0.074 ± 0.023(**)	< 0.03	0.06 ± 0.04
2021.8	0.26 ± 0.11	0.31 ± 0.09	0.31 ± 0.06
2052.94	1	1	1
2089.7	0.64 ± 0.17	0.61 ± 0.14	0.66 ± 0.08

Table 2: The relative intensities of the weak γ-lines from ^{214}Bi in the energy region from 2000 to 2100 keV are calculated with respect to the line at 2052.94 keV. A comparison between the expectations from the Table of Isotopes, the measurement and the simulation is made.
(*) Note that the intensities from the TOI can be compared with the measured intensities only in the case of the far geometry, where the TCS effect is negligible.
(**) The 2016.7 keV transition is not a gamma-line but an E0 transition (conversion electron or pair). No counts from this direct transition could be observed in our experimental spectrum, due to the short range of the electrons. For this reason a measured value compatible with zero, for the far geometry, is in perfect agreement with expectations.

The intensities of the five lines in the region 2000-2100 keV have been normalized to the intensity of the line at 2052.94 keV. In the case of the far geometry measurement (see Table 2), there is a good agreement between the relative intensities from the Table of Isotopes and the measured (and simulated) intensities. This was expected because in this case the summing effect is negligible.

In the case of the close geometry, the two lines at 2010.71 keV and 2016.7 keV show an increase in the relative intensity (by a factor of 1.5 and 10.6 respectively) which is obtained only by putting the source close to the detector (in this case 3.4 cm instead of 18.4 cm). At this distance the summing effect plays a strong role.

The intensities of the other lines, as shown in Table 3, are still in agreement with the Table of Isotopes. According to the decay scheme of ^{214}Bi, they were not supposed to be affected by the true coincidence summing.

Close Geometry (source on the top of the detector cap)

Energy (keV)	Rel.Int.(TOI) (*)	Rel.Int.(Exp.)	Rel.Int.(Sim.)
2010.71	0.64 ± 0.17	0.97 ± 0.07	1.11 ± 0.13
2016.7	0.074 ± 0.023 (**)	0.79 ± 0.08	0.63 ± 0.09
2021.8	0.26 ± 0.11	0.26 ± 0.06	0.26 ± 0.06
2052.94	1	1	1
2089.7	0.64 ± 0.17	0.68 ± 0.06	0.58 ± 0.09

Table 3: The relative intensities of the weak γ-lines from ^{214}Bi in the energy region from 2000 to 2100 keV are calculated with respect to the line at 2052.94 keV. A comparison between the expectations from the Table of Isotopes, the measurement and the simulation is made. The discrepancy between the TOI values and the measured (and simulated) values for the lines at 2010.71 keV and 2016.7 keV is due to the different position of the source.
(*) See note in Table 2.
(**) See note in Table 2.

5 Conclusions

We presented the results obtained measuring the ^{214}Bi spectrum, with a high purity germanium detector, in the energy region around the the Q-value of ^{76}Ge neutrinoless double-beta decay (2039.006 keV). The ^{226}Ra source used for the measurements was positioned, in a first step, directly on top of the copper cap of the detector and, in a second step, 15 cm away from the copper cap.

The results of the measurements show that, if the source is close to the detector, the intensities of the weak bismuth lines in the energy region 2000-2100 keV are not in the same ratio as reported by the Table of Isotopes. Only with a simulation, which takes into account the True Coincidence Summing Effect and the position of the source with respect to the detector, it is possible to reproduce the measured intensities with good agreement.

The analysis [1, 2, 3, 4] of the data collected by the HEIDELBERG-MOSCOW experiment, yielding a first indication for the neutrinoless double beta decay of ^{76}Ge, shows that four ^{214}Bi lines are present in the energy region from 2000 to 2080 keV (many other strong lines from the same isotope are present in the spectrum), due to the presence of bismuth in the experimental setup, especially in the copper in the vicinity of the crystals.

The present measurement shows that the criticism raised in [6] regarding the analysis of [2, 3, 4] of the intensities of the weak bismuth lines between 2000 and 2080 keV is *not valid*. The effect of the distance between source and detector, as shown in this work, can affect strongly the intensities of some weak lines (in the geometry investigated here by a factor 1.5 for the line at 2010.71 keV and a factor 10.6 for the line at 2016.7 keV). Only with a careful simulation of the experimental setup, as it has been done in this work, and earlier in [3, 7], it is possible to correctly calculate the expected values for the line-intensities.

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